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INVESTIGATION OF THE MECHANISMS ASSOCIATED WITH GAS BREAKDOWN UNDER INTENSE OPTICAL ILLUMINATION

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<u>Investigation of the Mechanisms Associated with</u>

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I. SUMMARY

The Research Laboratories of the United Aircraft Corporation under the present contract are conducting experimental and theoretical investigations of the mechanisms responsible for gas breakdown with focused optical frequency laser radiation. At sufficiently high power densities, the focused radiation causes electrical breakdown (ionization) of the gas. Studies have been made of the growth and persistence of the ionized gas formed in the breakdown, and of the effect of this plasma on the transmission of subsequent laser pulses. The breakdown threshold, or minimum power density required to produce breakdown, has been studied as a function of: (1) gas species for both pure gases and gas mixtures, (2) gas pressure from atmospheric to 10^5 torr, (3) the wavelength of the laser radiation at 0.69 μ and 1.06 μ, and (4) the volume within which the breakdown is initiated. Existing theoretical models do not adequately describe the experimental results obtained, and further studies have been undertaken to determine the processes leading to gas breakdown by optical frequency radiation.

In the contract period covered by this report, the effects of the mode structure of the laser radiation source on the gas breakdown threshold have been studied. Experiments have also been performed using a Mach-Zehnder interferometer to observe the breakdown plasma density and to determine the persistence and growth rate of the associated blast wave.

Under the present contract the development of a high-power CO_2 laser with an output at 10.6-μ wavelength is being carried out. Studies of this laser in both cw and Q-switched operation have been made, using a rotating mirror as the Q-switch. For these experiments electrical discharge excitation has been employed, either dc or pulsed, the latter with a capacitor bank power supply. These studies are directed toward obtaining a 10.6-μ CO_2 laser system with sufficient power to cause gas breakdown. The measurement of the breakdown threshold of gases at 10.6 μ is of importance for determining the limits of transmission of CO_2 laser radiation through a gas atmosphere. The breakdown threshold at 10.6 μ will also be compared with the threshold data obtained previously using ruby and neodymium laser radiation to determine further the wavelength dependence of the breakdown threshold and to help clarify the

mechanisms which cause the gas breakdown. In Part II the results of the previous studies of gas breakdown by optical frequency radiation under Office of Naval Research sponsorship are described, and the measurements carried out during the present contract period are outlined. In Part III studies of the effects of the laser radiation mode structure on the gas breakdown threshold are described. The interferometric investigations of the gas breakdown blast wave are discussed in Part IV. In Part V investigations directed toward the development of a high-powered CO_2 laser system for the study of gas breakdown phenomena at 10.6 μ are described, and in Part VI the results of these several studies, as well as the previously obtained results, are outlined along with the program for the next contract period.

II. INTRODUCTION

Under the sponsorship of Office of Naval Research Contract Nonr-4299(00), the present contract Nonr-4696(00), and in a parallel Corporate-sponsored program, the United Aircraft Research Laboratories are engaged in studies of the interaction of high-intensity optical frequency radiation with gas atoms. The breakdown threshold, or minimum radiation power density required to ionize the gas, has been investigated using ruby and neodymium laser radiation at output wavelengths of 0.69 μ and 1.06 μ, respectively. In order to obtain an understanding of the mechanisms leading to gas breakdown, the threshold required for breakdown has been examined as a function of various experimental parameters. From these studies, the breakdown threshold electric field for the inert gases varies as the square root of the ionization potential divided by the electron-atom collision frequency, in agreement with a cascade breakdown process. Molecular gases, such as air and nitrogen, require somewhat higher threshold field strengths, indicating that the dissociation of the molecules or the availability of additional degrees of freedom (e.g., vibrational excitation) in some way inhibits the breakdown development. For all of the gases studied, the threshold varies inversely with the square root of gas pressure from atmospheric pressure to approximately 10^4 torr. A minimum in the breakdown threshold as a function of pressure was observed for breakdowns produced within large focal volumes and occurs at 2×10^4 torr for argon and 5×10^4 torr for helium for breakdown with neodymium radiation. With ruby radiation the minimum was also observed but only in argon and occurred at a higher pressure of 5×10^4 torr.

Experiments were conducted to determine the dependence of the breakdown threshold on the focal volume within which breakdown is initiated. The focal volume is characterized by the diffusion length, Λ, and the threshold was found to decrease with increasing Λ, indicating that a diffusion-like loss dominates the breakdown process. The decrease in threshold with increasing Λ was observed in all of the gases studied over the pressure range from atmospheric pressure to 10^5 torr. The diffusion lengths in these experiments ranged from 1.6×10^{-3} cm to 3.0×10^{-2} cm, and the breakdown threshold field strengths for the largest focal volumes were an order of magnitude lower than those for the smallest focal volume. This diffusion-like loss process, although it dominates the breakdown development, is not accounted

for in any existing theories of the gas breakdown process, and points out the serious discrepancy that exists between the theoretical models and the experimental data of gas breakdown with optical frequency radiation. Studies of breakdown threshold in Penning mixtures (argon and neon) suggest that the diffusion-like loss process observed experimentally is radiation transport of the excitation energy. The addition of a small percentage of neon to argon reduced the threshold by a factor of two and decreased the Λ dependence of the gas mixture breakdown threshold. In the argon-neon Penning mixture, an excited neon atom transfers its excitation energy to argon in a collision ionizing the argon atom as a result of the near resonance between the excitation potential of neon and the ionization potential of argon. The gas breakdown experiments with Penning mixtures suggest that atom excitation retards the development of breakdown and that radiation transport of this excitation energy, inhibited by resonant radiation trapping, is the diffusion-like loss process which affects the breakdown threshold. This result may also explain the reason for the higher breakdown thresholds observed with molecular gases; vibrational excitation of the molecules could slow the development of breakdown, and radiation of this energy would constitute a loss process.

The dependence of the breakdown threshold on the frequency of the radiation was obtained from data with ruby (0.69-μ wavelength) and neodymium radiation (1.06 μ). At low pressures (< 10^4 torr), the higher frequency ruby radiation required larger field strengths to produce breakdown than were required with neodymium radiation. At higher pressures (> 10^4 torr), the thresholds with neodymium and ruby radiation were nearly equal as a result of the minimum in the threshold as a function of pressure which occurs at a lower pressure with neodymium radiation than with ruby. The frequency dependence of the breakdown threshold is in qualitative agreement with a cascade ionization process where the rate of energy addition is inversely proportional to the square of the radiation frequency.

For a cascade ionization, an initial electron is required in the focal region to start the cascade process. The source of the initial electron is believed to derive from easily ionizable impurity atoms present in the test gases. Experiments were performed where cesium, as an "impurity" atom with a low ionization potential, was added to argon. The threshold was reduced in these experiments by the added cesium, showing that easily ionized impurities can affect the development of breakdown. Studies of breakdown with an initial preionization in the focal region were also conducted. The laser radiation was focused in a dc electrical discharge which provided the initial preionization. The threshold with the preionization was reduced by a factor of two below that of the gas in the absence of the dc discharge, a result again in agreement with a cascade ionization process.

The photon energy of optical frequency radiation is 1-2 eV and only 10 or so photon interactions are required to ionize the inert gases or air. Because of the small number of absorptions required, the rate of energy gain may be greater than the rate for a process involving many photon interactions, as in the "microwave" absorption process. To test the effect of the relative size of the radiation photon energy and the atom ionization potential, gas breakdown in cesium vapor was studied using ruby and neodymium radiation. Cesium (ionization potential 3.9 eV) requires

only 3 ruby or 4 neodymium photons of energy for ionization. From the experimental results, extrapolating the cesium breakdown data to atmospheric pressure and taking into account the difference in ionization potential and collision frequency, the breakdown threshold of cesium was found to be an order of magnitude lower than that of the inert gases, showing that the number of photons required for ionization is a significant factor in determining the breakdown threshold. The breakdown threshold of cesium with either ruby or neodymium radiation was the same, in contrast to the frequency dependence observed with the other gases. This result further demonstrates the importance of the photon energy-ionization potential ratio in the gas breakdown process.

The experimental results of gas breakdown studies with the inert gases, namely: the pressure dependence, frequency dependence, the effect of an initial ionization, and the dependence on the ionization potential and collision frequency of the gas, all agree qualitatively with a cascade ionization process. The quantitative agreement, however, is poor, and based on the experiments with low ionization potential gases, this discrepancy appears to be the result of a more efficient energy absorption mechanism than that calculated for a many photon interaction process. This would account for the lower thresholds observed in the large focal volumes and together with the suggested radiation transport model would explain the focal volume-surface area ratio dependence of the breakdown threshold.

The plasma produced by gas breakdown has been studied experimentally to determine the persistence and spatial extent of the plasma and its effect on the attenuation of subsequent laser pulses. At laser powers slightly above threshold, over one-half of the laser pulse energy is absorbed by the breakdown plasma, and instantaneous attenuations as large as 90 per cent are observed. A He-Ne laser beam transmitted through the breakdown region was attenuated and severely modulated for times of the order of milliseconds after breakdown initiation. The attenuation experiments show that when breakdown occurs, subsequent laser pulses even milliseconds later will be only partially transmitted through the breakdown region.

The blast wave generated by breakdown was studied using streak and framing photography of the luminous front. The luminous growth was observed to grow toward the laser focusing lens with velocities of the order of 10^7 cm/sec. Two mechanisms have been proposed to explain the rapid expansion: (1) a radiation-supported blast wave, and (2) a gas breakdown propagation where, as the incident power increases in time, the intensity ahead of the focus becomes sufficient to generate breakdown in the un-ionized gas. If the first of these mechanisms is dominating the plasma growth, then the equilibrium temperature can be calculated based on the expansion velocity. With the second mechanism, the luminous growth is controlled primarily by the rise time of the laser pulse and the solid angle of the focusing lens, and thus is independent of the plasma temperature. The second mechanism has been observed experimentally for breakdown with long focal length lenses. In these experiments separate and distinct breakdowns were observed to occur within the breakdown region in a time-position sequence similar to the luminous growth observed for breakdown with shorter focal length lenses. These results show that both mechanisms can be important in the plasma expansion, and further studies are required to

determine whether the temperature of the breakdown plasma can be reliably evaluated from the breakdown expansion velocity.

The details of these results have been covered in the Final Report C-920088-2, under Office of Naval Research Contract Nonr-4299(00) and in the semiannual reports, (December, 1964; August, 1965; and January, 1966) and the Final Report of August, 1966, under Office of Naval Research Contract Nonr-4696(00). Further discussions of the observed phenomena have been reported in the open literature in Proceedings of the Sixth International Conference on Ionization Phenomena in Gases, Paris, France, July 8 - 13, 1963; Physical Review Letters, Vol. 11, No. 9, November, 1963; Physical Review Letters, Vol. 13, No. 1, July, 1964; Proceedings of Physics of Quantum Electronics, McGraw-Hill Book Company, New York, 1966, p. 509; Physical Review Letters, Vol. 16, No. 24, June, 1966; and in Applied Physics Letters, to be published August 1, 1967.

During this report period investigations have been made to evaluate the effects of the mode structure within the laser beam on the breakdown threshold of gases. In addition, the details of the expansion of the breakdown plasma have been studied using a Mach-Zehnder interferometer to examine the blast wave growth and to investigate the long-time effects of the breakdown on the transmission of laser radiation. Central to the investigations under the current contract is the development of a high-powered CO_2 laser with an output of 10.6 μ. Both pulsed and dc excitation of the laser medium have been investigated, and measurements of the laser output have been made for cw and Q-switched operation of the laser. These investigations are directed toward obtaining high-power, 10.6-μ radiation for breakdown experiments in order to extend the frequency range of previous studies and to evaluate the limitations caused by gas breakdown on the atmospheric transmission of high-powered CO_2 laser radiation.

III. EFFECTS OF MODE STRUCTURE ON GAS BREAKDOWN THRESHOLD

Theoretical models proposed to explain gas breakdown, while showing qualitative agreement with most of the experimental results do not explain adequately the quantitative experimental data. In particular, no theory has been developed which accounts for the strong focal volume dependence of gas breakdown threshold described in Ref. 5. The breakdown threshold electric field strength decreases as the focal volume to surface ratio is increased. Theoretical models have been developed which predict threshold field strengths slightly higher than those observed experimentally with small focal volumes, and for these focal volumes the theories are in reasonably good agreement with experimental data.[12,13] These theories, however, do not consider any focal volume dependence, and since the experimental threshold field strengths required for breakdown for the larger focal volumes studied are more than a factor of 10 lower than those required for the smallest focal volumes, these theories predict threshold field strengths more than a factor of 10 higher than the observed experimental data. Two possibilities exist for the discrepancy between theory and experiment: (1) The threshold field strengths calculated from the experimental data are not the field strengths responsible for gas breakdown, or (2) the

radiation-gas atom interaction mechanism proposed in the theories is in error.

In the experiments an average radiation field strength in the focal region is determined from calorimetric energy measurement of the laser pulse, a time-integrated intensity profile (resolution 0.5 nsec), and an average focal area. The lasers used in the experiments operate in a multiple mode configuration, and the many modes present can constructively interfere in the focal region. Such interference can result in instantaneous electric field intensities several orders of magnitude larger than the average value of the focused laser radiation.[14] The interference of the modes leads to a complex spatial and temporal pattern which depends critically on the phase relations between the various modes, and an exact treatment of this problem cannot be carried out. The large instantaneous intensities resulting from this local interference, rather than the average value measured experimentally, could ionize and support the breakdown.[13,15] To determine the effects of the mode structure of the laser radiation on gas breakdown, experiments were undertaken with two different types of laser pulses: (1) multiple mode neodymium laser radiation with a temporally smooth (on a 0.5 nsec scale) pulse as used in previous gas breakdown experiments,[1-10] and (2) a neodymium laser pulse whose various modes were locked in phase giving a train of extremely short duration radiation spikes whose intensities are at least two orders of magnitude greater than the average intensity of the laser pulse. The mode-locked laser pulses were produced by bleachable dye Q-switching a neodymium laser, the resulting phase locking of the laser cavity modes giving rise to the short duration spikes within the pulse. Comparison of the gas breakdown threshold with these two types of pulses was then used to determine the effects of laser pulse mode structure on gas breakdown threshold.

Shown in Fig. 1 is a schematic of the neodymium laser system used to produce the laser pulses for these experiments. Using a saturable dye Q-switch (Eastman Kodak 9740), the laser output consists of a regular series of very short pulses whose peak intensities greatly exceed the pulse average. For this laser cavity configuration, the pulse train is contained in a smooth envelope whose half-width is 40 nsec. The pulse train is the result of phase locking of the many axial modes of the laser and occurs if the relaxation time of the saturable dye is much shorter than the laser cavity transit time. The individual pulses in the train occur at intervals equal to the laser cavity transit time (7 nsec in the present experiments) and have pulse widths with an upper limit of 1.5×10^{-10} sec, as measured by Stetser and DeMaria,[16] the measurement limited by the detector response. For the present experiments the detector system consisted of an ITT photodiode (response time 0.35 nsec) coupled to a Tektronix 519 oscilloscope (response time 0.4 nsec) giving an over-all system response time of 0.5 nsec, so that the known short duration of the individual pulses is not resolved. A photodiode is used to observe the laser pulse after it has passed through the lens focus, and the resulting signal is displayed starting at the beginning of the oscilloscope sweep. The incident laser pulse waveform, monitored by a second photodiode, is electronically delayed by 60 nsec and displayed on the same oscilloscope trace. The incident and transmitted laser pulses are thus presented on the same single beam oscilloscope and appear as shown in Fig. 1. For laser powers below gas breakdown threshold (atmospheric pressure air was used in these experiments), the incident and transmitted pulses, as observed with the two

diodes, are of equal amplitude and time history. However, at a power level just above threshold, as shown in Fig. 1, the laser radiation transmitted through the breakdown region is severely attenuated during the later portion of the laser pulse. Using the same neodymium laser system, but replacing the saturable dye with a Kerr cell-polarizer Q-switch, as shown in Fig. 2, a temporally smooth laser pulse with the same half-width as the mode-locked pulse train was obtained. Using the same photodetection system, at a laser power level just above threshold, the same attenuation of the transmitted pulse obtained with the mode-locked pulse is observed. A photograph of the incident and transmitted temporally smooth laser pulses is shown in Fig. 2.

From Figs. 1 and 2 for both the smooth and mode-locked pulses, the time required for the start of absorption (a measure of the time of breakdown development) is the same as is the envelope time history of the attenuated beam. The time-averaged power density of the mode-locked pulse train at breakdown threshold of atmospheric pressure air is 10^{11} watts/cm^2, the laser power obtained by dividing the total energy of the pulse train by the time envelope half-width (40 nsec). With the temporally smooth pulse of Fig. 2, the breakdown threshold is 10^{11} watts/cm^2, the same as the average power density of the mode-locked train. Assuming that the width of the short pulses of the mode-locked train is 0.1 nsec (based on the upper limit measurement of Ref. 16) and using the measured values of the pulse train energy, number of pulses, and beam divergence, the peak power density at breakdown threshold of atmospheric air is 10^{13} watts/cm^2.

While the train of short pulses of the mode-locked laser radiation has peak powers two orders of magnitude greater than the average, the average power required to produce breakdown is identical with the threshold power for a temporally smooth laser pulse. The temporally smooth laser pulse consists of many axial modes which can constructively interfere and lead to regions of high localized intensities in the focal spot. In this case the mode beating is a statistical process, and interference depends critically on the phase relations between the various modes. As a result, in general, not all of the modes present can constructively combine to produce intensity fluctuations. With the mode-locked laser pulses, however, the various modes are locked in phase by the Q-switching technique and contribute constructively to the laser radiation intensity. Further, the intensity fluctuations of less than 0.1 nsec duration of the mode-locked pulses are readily observed with the photodetectors used, and no evidence for such high intensity fluctuations is observed with the normal multiple-mode laser pulse. Since the average power density required to produce breakdown is the same with both types of laser pulses, it is concluded that temporal fluctuations resulting from mode beating are unimportant in determining gas breakdown and that the average power density as measured experimentally is the determining factor in the development of gas breakdown. The experimental results also indicate that the radiation-atom interaction mechanism which leads to gas breakdown averages the energy input over a time long compared to the 7 nsec between the individual mode-locked pulses. Based on these experimental observations, it is concluded that the breakdown of gases by optical frequency radiation is not affected by statistical fluctuations in the laser beam intensity, and the threshold is determined by the average intensity, averaged over a time of the order of 10 nsec.

A further conclusion can be drawn from these experimental observations; it appears that the theoretical model of multiple photon absorption proposed to explain gas breakdown[15,16,17] cannot be valid. The multiple photon process is a direct radiation gas-atom interaction in which the n photons required to ionize the atom are absorbed simultaneously, with the result that the ionization rate is proportional to the nth power of the radiation power density. Thus the multiple photon absorption theory predicts that the ionization rate of air with neodymium radiation should depend on the 16th power of the laser beam intensity, and because of this strong intensity dependence, even a small change in the mode-beating pattern would result in a large change in the breakdown threshold. Experimentally the average power density required for breakdown is independent of the imposed large temporal fluctuations of the mode-locked laser pulses, and therefore, the multiple photon ionization of gas atoms does not contribute significantly to the ionization growth and breakdown development.

IV. BLAST WAVE GENERATED BY GAS BREAKDOWN

Streak and framing photography have been used to study the expansion of the breakdown plasma luminosity, as reported in previous progress reports.[4,5] During this report period further studies of the expansion were undertaken using a Mach-Zehnder interferometer to examine the shock wave growth in greater detail. The luminous front of the breakdown plasma and the blast wave will coincide for only a short time, and thus only during the initial stages can the blast wave growth be studied by observing the luminous front. With interferometry, the growth of the blast wave can be determined more accurately and over a longer time period without reference to the plasma luminosity. In addition, the interferograms show the persistence of the breakdown plasma and determine over what time period the breakdown will have an effect on the propagation of subsequent laser pulses.

A schematic of the experimental setup is shown in Fig. 3. The interferometer consists of a pair of 2-inch-diameter beam splitters and two fully reflecting mirrors. A lens is used to focus the laser radiation causing breakdown in one path of the interferometer. The interferometric pattern was recorded with an image converter camera, permitting time resolution of the blast wave growth.

In an attempt to study the breakdown plasma at early times, a portion of the neodymium laser radiation, which produced the breakdown, was used to illuminate the interferometer. A partially reflecting mirror directs a fraction of the laser beam into the interferometer, and a narrow band pass filter, centered at 1.06 μ, was used to reduce the intensity of the breakdown plasma. However, in these early time experiments the radiation was completely absorbed by the breakdown plasma, and consequently, no fringe pattern was observed in the breakdown region. This result was not entirely unexpected, since as shown in Fig. 2, the focused laser radiation which produces the breakdown is severely attenuated during the latter portions of the laser pulse. By delaying in time that fraction of the laser pulse used to illuminate the interferometer, experiments were performed to examine the blast wave

growth at times well after the breakdown initiation. By using mirrors to reflect the radiation, a 100-foot path between the laser source and the interferometer was obtained, resulting in a 100-nsec time delay between breakdown and the interferometric observations. Even on this time scale, the breakdown plasma, while having expanded considerably, was still opaque to the observing radiation, and no measurements were possible. It is apparent from these results that, due to the high electrical conductivity of the plasma produced, the breakdown plasma will attenuate successive laser pulses of a pulse train for times greater than 100 nsec after breakdown.

For studies of the breakdown plasma at still later times, a BH-6 mercury arc lamp was used for the interferometer light source. Because of the intense radiation emitted by the breakdown plasma and the short exposure times required to resolve the blast wave position, white light rather than monochromatic interferograms were used, giving 8 or 10 useful fringes. A sequence of white light interferograms is shown in Fig. 3, each interferogram labeled by the appropriate time after breakdown initiation. The exposure time for the individual frames is 10 nsec. The plasma luminosity overshadows the interferometer light in the first frames, and only after one microsecond following breakdown can the shock wave be seen ahead of the luminous core. After four microseconds, the axial and transverse growth of the plasma are comparable in size, and the blast wave has assumed a spherical shape. In the interferograms a fringe shift to the left denotes a density increase from atmospheric pressure air. Three microseconds after breakdown, the density jump across the shock wave is observed as a fringe shift to the left. Toward the center of the breakdown plasma, the fringe pattern shifts toward the right due to the high temperature and thus lower density of the plasma core. The fringe shift associated with the hot plasma at the center is actually greater than the positive (leftward) shift of fringes resulting from the density jump at the shock wave and indicates an index of refraction less than one associated with a high electron density. Since the breakdown plasma is spherical, inversion of the interferograms to obtain the plasma index of refraction as a function at position is extremely difficult, and since two wavelength interferometry is required for separation of the atomic and electronic contributions, quantitative analysis of the interferograms was not undertaken.

Ten microseconds after the breakdown formation, the blast wave is approximately two cm in diameter and is expanding at a Mach number of approximately two. The last frame of Fig. 3 is an interferogram of the breakdown region 100 microseconds after breakdown and shows a region of heated gas which appears to be making the transition from a laminar to a turbulent regime. In Ref. 3, a cw helium-neon laser directed across the breakdown plasma was focused in the breakdown region, and severe fluctuations of the transmitted intensity were recorded several milliseconds after breakdown. Based on the interferograms, this attenuation is not the result of residual ionization but is the result of refraction of the beam by the turbulent, heated gas.

The time history of the blast wave generated by gas breakdown can be analyzed following the treatment of G. I. Taylor.[19] The Taylor strong blast wave theory assumes a similarity solution for a blast wave generated by the instantaneous addition of energy to an infinitely small volume. The theory assumes similarity

forms for the velocity, temperature, and density profiles, with the similarity variable determined from the conservation of energy, momentum, and mass. The theory assumes a perfect gas with constant fluid properties and, in addition, assumes that there are no energy losses (such as radiation) from the blast wave. From the Taylor theory, the radial position of the spherical blast wave is given as a function of the energy and original gas density in the form

$$r = S(\gamma)\ (\epsilon/\rho)^{1/5}\ t^{2/5} \tag{1}$$

where $S(\gamma)$ is a numerical constant whose value is close to unity, r is the radial position at time t, γ is the specific heat ratio, ϵ is the total energy of the gas, and ρ is the initial density. The theoretical model would seem to be applicable to the breakdown blast wave, since the laser radiation energy is absorbed by the gas in a short time and within the small focal volume. Plotted in Fig. 4 is the radial expansion of the gas breakdown blast wave as a function of time determined from the interferometric photographs of Fig. 3 together with the theoretical expansion given by Eq. 1. Both the axial (toward the focusing lens direction) and transverse positions of the blast wave are plotted with the origin of breakdown as the initial zero position. The total energy of the breakdown plasma was evaluated from the difference in incident and transmitted laser energy determined from curves similar to those of Fig. 2. The agreement between theory and experiment is quite good, particularly for the transverse growth and the blast wave velocity (slope of the axial and transverse growth). The displacement of the axial expansion from the theoretical growth is due to the rapid initial expansion of the plasma toward the focusing lens during the laser pulse and consequent displacement of the effective blast wave origin. If the center of curvature of the blast wave rather than the position of the start of breakdown is taken as the origin, the axial growth rate is also in agreement with the theory within 5 per cent. The energy associated with the blast wave was experimentally varied by changing the laser radiation intensity, and over the experimentally available range of a factor of four in energy absorbed, excellent agreement with Eq. 1 was obtained. From these experimental observations several conclusions can be drawn. (1) The plasma generated by breakdown will severely attenuate subsequent laser pulses at least 100 nsec after breakdown due to absorption by the plasma. (2) The blast wave (although not necessarily the luminosity growth) is adequately described by the Taylor blast wave theory, and therefore, the growth rate, as well as the size of the plasma region at late times, can be predicted by this theoretical model. (3) A turbulent heated gas persists in the breakdown region 100 microseconds after breakdown, and from the He-Ne attenuation experiments, this turbulent heated gas will refract and modulate subsequent laser pulses for times as long as milliseconds after breakdown.

V. CO_2 LASER INVESTIGATIONS

Under the present contract investigations of the CO_2-N_2-He laser with an output wavelength of 10.6 μ are being carried out. Among other applications, this

infrared laser is of practical importance for the development of "optical" radar systems. The studies to date have been involved with the development of a high-power CO_2 laser of sufficient intensity to generate electrical breakdown of gases. To obtain a better understanding of the CO_2 laser system for optimization of power output, both continuous and Q-switched laser operation have been investigated under continuous dc and pulsed capacitor discharge excitation conditions.

1. Dc Electrical Discharge CO_2 Laser

Cw Operation

The CO_2-N_2-He laser system constructed for these experiments is shown schematically in Fig. 5 and consists of a water-cooled $2\frac{1}{2}$-meter-long pyrex tube with a metered flowing gas system. A dc power supply, capable of delivering 200 milliamperes at 30 kilovolts, is used to produce the excitation discharge between the uncooled copper electrodes, and infrared transmitting sodium chloride flats form the gas seal on the ends of the tube. A 2-inch-diameter gold-coated mirror, mounted on a variable speed motor capable of rotational speeds up to 20,000 rpm, is employed for Q-switching, and the output mirror of the laser cavity is clamped in a two-axis pivot Lansing mount for ease of alignment. The entire laser system--output mirror, discharge tube, and rotating Q-switch--is mounted on a 10-foot-long aluminum box beam for rigid support.

The initial experiments with this laser system involved variation of the operating parameters of the laser to determine the optimum conditions for maximum cw laser output power. The optimum cavity conditions for this CO_2 laser were a 99 per cent reflectance, ten-meter radius of curvature gold-coated mirror at one end of the laser cavity with a flat 65 per cent reflectance dielectric-coated output mirror at the other. Hole coupling of the laser beam through 1/4-, 1/2-, and 3/4-inch-diameter holes in gold-coated flat mirrors resulted in an output power lower than obtained with the 65 per cent reflectance dielectric reflector. Output mirrors with a reflectance of 4 per cent, 14 per cent, and 85 per cent also produced a low cw output laser power. Both one-inch- and two-inch-diameter discharge tubes were used, and the optimized laser power output was found to be independent of tube diameter. The one-inch-diameter system was selected for the laser investigations because the power output is a function of the gas flow rate through the discharge tube and the flow rates through the smaller bore tube are greater for a given capacity exhaust pump. The optimum gas mixture was found to 13 per cent CO_2, 17 per cent N_2, and 70 per cent He. Although the percentages of the three gases must be carefully controlled for optimum output power, the total gas pressure of the discharge was not critical in the range of 3-10 torr. For the dc excitation experiments a constant voltage cw power supply was used with a 70 kΩ ballast resistor connected in series with the discharge in order to limit the discharge current. The optimum output power from the laser was obtained with a current of 80 milliamperes at 15 kilovolts across the $2\frac{1}{2}$-meter-long discharge. Lower currents slightly reduced the output power, whereas currents of the order of 120 milliamps resulted in a significantly lower output power.

Under the optimized conditions as described above, 125 watts cw power was obtained with this laser. Due to the effects of discharge tube heating, deterioration of the sodium chloride flats and slight misalignment of the optics, typical output powers were in the range of 80 watts. Based on this cw power output, an estimate of the power obtainable from Q-switched operation can be made. The power obtainable from the cw operation of the laser is given by the product of the net population inversion and the laser photon energy, divided by the relaxation time of the upper laser level,

$$P_{cw} = \frac{N\,h\nu}{\tau} \tag{2}$$

where P_{cw} is the cw power, N is the net population inversion, $h\nu$ is the energy of the photon, and τ is the lifetime of the upper laser level. In Q-switched operation the inverted population can be depleted in a much shorter time and the output power is

$$P_Q = \frac{N\,h\nu}{T} \tag{3}$$

where T is the width of the Q-switch pulse. The ratio of the Q-switched to cw power is thus

$$\frac{P_Q}{P_{cw}} = \frac{\tau}{T} \tag{4}$$

While the lifetime of the upper laser level of CO_2 is of the order of milliseconds,[20] the width of the Q-switched pulse is a function of the speed of the rotating mirror, the reflectance of the mirrors, the length of the cavity, etc., and can be expected to be of the order of a few hundred nanoseconds. Thus the Q-switched power can be as much as 10^4 times greater than the cw power of the laser. This simple analysis cannot predict accurately the Q-switched power, since it ignores the effects of other levels of the excited molecule which may contribute to lasing in the cw case but do not couple rapidly enough to contribute to the Q-switched laser pulse.[21] Despite such limitations, it is not unreasonable to expect a P_Q/P_{cw} ratio of 10^3, i.e., a Q-switched output of approximately 80 kilowatts from the $2\frac{1}{2}$-meter, 80-watt cw CO_2 laser.

Q-Switched Operation

A variable speed rotating mirror was used for Q-switching the CO_2 laser. Rotational speeds of 250 cps produced Q-switched pulses with an energy content of one to two millijoules. The output pulses waveform was examined using a gold-doped

germanium infrared photodetector with a response time of approximately 100 nanoseconds. A low intensity lase was observed preceding the giant pulse, this prelase lasting for as long as 10 to 20 microseconds. Such prelase operation is characteristic of a slow Q-switching device and reduces the inversion available for the giant spike, resulting in a long pulse of low peak power. In these experiments the rotating mirror had a radius of curvature of 10 meters and thus forms a resonant optical cavity over a wider misalignment range (and consequently over a larger fraction of the mirror rotation time) than a flat mirror. However, replacement of the curved mirror with a gold-coated flat did not reduce the prelasing appreciably, and an alternate cause is indicated. In cw operation, the mirror could be rotated ± 25 mrad on either side of optimum alignment and still obtain 20 per cent of the maximum cw laser output. A rotation of 25 mrad would displace the beam 6 cm in one traversal of the laser tube, and the only way for the laser to operate with this amount of misalignment is for the laser radiation to reflect (and probably multiply reflect) off of the inside tube walls. To reduce this effect, the inside wall of the tube was etched with a hydrofluoric acid solution, producing a frosted glass surface. With the frosted tube, mirror rotations of only ± 15 mrad reduced the laser power to one per cent of optimum output, showing that reflections from the inside tube walls of the discharge were responsible for the observed effect. Q-switching of the laser showed that the prelasing, while still present, was reduced to approximately two microseconds, an order of magnitude improvement over the unfrosted system. The energy contained in the prelase as well as that of the giant pulse are both recorded calorimetrically, and consequently, the power output from the Q-switched laser cannot be measured accurately. The Q-switched pulses obtained were 100-200 nsec half-width, the measurement limited by the detector response time. On the basis of these measurements, the Q-switched pulses have a power level of 10 to 20 kilowatts, well below the theoretical power predicted by Eq. 4 for an 80-watt cw laser. The reasons for the low Q-switched powers are believed to be the result of: (1) heating of the discharge tube by the dc excitation current, and (2) the prelase preceding the output pulse, which results in a reduced overpopulation and an inefficient Q-switch. The first of these effects indicates a significant difference between Q-switched and cw operation. In cw operation, over 10 per cent of the electrical energy input to the discharge is converted into laser radiation. When Q-switching, radiative output does not occur except during the short alignment time of the rotating mirror, and the discharge energy must be dissipated in the form of heat which in turn reduces the inversion efficiency of the laser system. That heating is detrimental to the laser performance is supported by the experimental observation that for optimum Q-switch operation the current of the discharge is only 40 milliamps, compared with the 80 milliamps optimum for cw operation. To reduce the heating effects of dc electrical excitation, the discharge tube has now been set up for pulsed operation. Even with pulsed excitation, however, prelasing still poses a problem to efficient Q-switching. A possible technique for elimination of the prelasing is the use of a passive Q-switch, either alone or in conjunction with a rotating mirror. Preliminary studies of passive Q-switching the CO_2 output which appear promising have been undertaken and are discussed later in the report.

2. Pulsed Electrical Discharge CO_2 Laser

With the dc-excited discharge laser, it was observed that within a one-to-two-minute time interval the cw laser power decreased as much as 20 per cent from its maximum output, obtained immediately after start-up. This effect is attributed to thermal heating of the discharge tube. In addition, the cw power output increases with exhaust pump speed, again because of thermal effects; the faster pump rate, in effect, thermally cools the gas discharge by purging the heated gas. As a result of the adverse effects of discharge heating, pulsed operation should result in higher output powers from the CO_2 laser. With a pulsed discharge it may be possible to alter the electron temperature without thermally heating the gas, and since electron-molecular collisions are the excitation mechanism in the CO_2 laser, the pulsed discharge should exhibit a higher laser gain.

A schematic of the laser system for pulsed operation is shown in Fig. 5. The discharge tube and optics are the same as used with the dc discharge. A one-microfarad, 25-kilovolt capacitor, triggered by a series spark gap, is discharged through the tube. The pulse current is varied by altering the resistance in series with the discharge tube. Under identical conditions of flow rate and gas composition, the average power output from the pulsed laser is 500 watts for a pulse length of 200 microseconds and is a factor of six greater than the cw power obtained from the dc discharge laser. The output laser pulse is shown in Fig. 6 along with the applied excitation voltage pulse. The laser pulse width can be changed by variation of the gas composition (i.e., change in resistance of the discharge) or by altering the current-limiting resistor (0-2 kΩ in the present experiments). Qualitatively the laser pulse width increases with circuit resistance, while the output power level decreases. The optimum conditions for maximum output under pulsed operation have not been fully investigated, and additional studies are now in progress. In this regard it is significant to note that the gain of the laser under present conditions is quite high, and it was experimentally observed that the laser has sufficient gain to lase even without the use of external mirrors. Based on this result, further increases in gain of the laser system may be limited by superfluorescence, and increases in power may require an oscillator-amplifier configuration.

Q-Switch Operation

In order to Q-switch the pulsed CO_2 laser, it is necessary to synchronize the discharge excitation pulse with the rotating mirror; for this purpose a magnetic pickup was inco rated on the rotating mirror. The signal from the magnetic pickup was used to tri r a variable delay timing unit which in turn fired the spark gap of the capacitor circuit. Using this system, the pulse discharge could be synchronized with the alignment of the rotating mirror by altering the time delay of the variable delay timing unit. Q-switched laser pulses during the pulsed discharge have been obtained with this system. It was observed that approximately two microseconds of prelase occurred prior to the giant pulse, just as with dc excitation of the discharge. In the case of the pulsed Q-switched laser, however, the energy per

pulse was five to seven millijoules, significantly greater than the energy obtained with the Q-switched dc electrical discharge laser. Because of electrical noise from the pulsed laser, the giant spike could not be resolved on a fast oscilloscope sweep. Consequently, the pulse width could not be determined, and the power output for Q-switched pulsed operation is not known. It is reasonable to expect that the pulse widths for the two systems will be comparable. However, this will be experimentally examined during the next report period. Since the energy per pulse is a factor of five greater than with dc electrical discharge excitation, the system exhibits greater gain and should produce significantly higher peak power Q-switched laser pulses.

3. Passive Q-Switch for CO_2 Lasers

Because of the prelasing before the alignment of the rotating mirror, the Q-switch laser does not operate as efficiently as possible. One technique for eliminating the prelasing is the use of a passive or bleachable Q-switching device, such as the liquid dyes currently used with optical frequency lasers. For a passive Q-switch, the material must have an absorption at 10.6 μ and must absorb sufficiently rapidly to produce fast shuttering. The absorption bands at 10.6 μ are predominately due to vibrational transitions of molecules, and it appears that, at this wavelength, a gaseous system will be more appropriate than the liquid passive Q-switches used for optical wavelength lasers.

Preliminary investigations during this contract period have shown that such a passive Q-switch for the CO_2 laser can be made. In particular, propane, which has a moderate absorption at 10.6 μ, has been used to passively Q-switch the CO_2 laser. A three-inch-long gas cell with sodium chloride flats was evacuated and placed internal to the laser cavity. With the dc electrical discharge turned on, propane was then added to the cell. As the pressure of the gas increased, the cw laser output decreased, and at a pressure of approximately one atmosphere, random-spiked output from the laser was observed. The intensity of the spikes was significantly greater than the cw output, but no quantitative data is as yet available.

The propane cell was also used in conjunction with the rotating mirror. With approximately one-third atmosphere of propane in the cell, the prelasing, always present in the previous Q-switching studies, was eliminated. If the action of the propane is a true bleachable Q-switching, rather than an attenuation of the cavity radiation to near threshold conditions, then the energy available for the giant pulse should be greatly increased by the elimination of the prelase, and further studies with the propane Q-switch are currently in progress. Other gases may prove to be more efficient than propane, and experiments with other gases for passively Q-switching the CO_2 laser are planned for the near future.

VI. THIRTY-MONTH STATUS EVALUATION AND FUTURE PROGRAM

1. Thirty-Month Status Evaluation

During the thirty months of this contract, the following specific objectives have been accomplished:

a. Studies of gas breakdown by optical frequency radiation have been carried out in argon, helium, neon, and air over the pressure range from atmospheric pressure to 1×10^5 torr using the 0.69-μ and 1.06-μ radiation from high-intensity ruby and neodymium lasers, respectively. With both ruby and neodymium radiation, breakdown in air was observed to require the highest field strength with successively lower field strengths required for the breakdown in neon, helium, and argon. At low pressures with either ruby or neodymium laser irradiation, the breakdown threshold was observed to decrease with pressure varying approximately as $1/\sqrt{P}$.

b. Measurements have been made of the attenuation of the incident giant laser pulse by the breakdown plasma. For beam intensities slightly above the breakdown threshold, it was observed with both ruby and neodymium radiation that more than half of the laser beam energy can be absorbed in the plasma produced by the breakdown and that over 90 per cent attenuation of the laser beam can occur during the later portions of the giant pulse. Measurements of the attenuation of an optical beam by the breakdown plasma at times following the incident giant pulse have been carried out using the cw beam from a helium-neon laser and show that the same 90 per cent attenuation is present for times of the order of milliseconds after the formation of the plasma. These measurements demonstrate the long-time effect of gas breakdown on the transmission of subsequent laser pulses.

c. Measurements have been made to examine the effects of diffusion-like losses on the breakdown threshold by varying the focal volume within which the breakdown is formed. The focal volume is characterized by the diffusion length, Λ, and studies have been made of the dependence of the breakdown threshold on Λ over the range 1.6×10^{-3} cm $\leq \Lambda \leq 3.0 \times 10^{-2}$ cm. With both ruby and neodymium radiation, the breakdown threshold for all of the gases studied is inversely related to Λ; i.e., breakdown within small focal volumes requires a larger optical frequency electric field than is necessary for larger volumes. These measurements have been carried out from atmospheric pressure to 1×10^5 torr, and at all pressures the same effect is noted. The dependence of the breakdown threshold on the dimensions of the breakdown volume implies that even at pressures as high as 1×10^5 torr, diffusion-like losses play a

significant role in the development of optical frequency breakdown and that the loss-free breakdown threshold lies at still lower electric field strengths. For the smaller focal volumes, the threshold varies approximately as Λ^{-1}. While for the largest focal volumes studied the threshold varies as $\Lambda^{-1/2}$ showing a decrease in the volume dependence and indicating that the loss-free threshold is being approached.

d. In the experiments with neodymium irradiation, at the larger focal volumes with both helium and argon a pronounced minimum has been observed in the breakdown electric field vs. pressure curves. With ruby radiation no minimum is observed for helium and that for argon is less distinct and shifted to higher pressures.

e. Using the breakdown data obtained with ruby and neodymium laser irradiation, the frequency dependence of the breakdown threshold has been evaluated. For either argon, helium, or air the lower frequency neodymium radiation gives a lower breakdown threshold than for ruby at low pressures. At high pressures the neodymium breakdown threshold of helium approaches the ruby threshold, while in argon the neodymium threshold is even larger than obtained with ruby as a result of the minimum observed with neodymium. For air the ratio of the neodymium to ruby breakdown threshold remains approximately constant over the pressure range studied.

f. Theoretical studies have been carried out which show that existing classical models of the breakdown process are not adequate to explain the phenomena observed at optical frequencies. Multiple-photon theories recently proposed are unable to predict the magnitude of the E field required for breakdown or the pressure and volume dependence obtained experimentally. Calculations of the inverse bremsstrahlung cascade theory of the breakdown process have been carried out for optical frequencies where the photon energy is greater than the classically calculated electron oscillation energy and show that an electron exchanges energy with the applied electromagnetic field in increments of the photon energy. This result differs in kind from that obtained using the classical microwave theory and offers an experimental test to examine the validity of the inverse bremsstrahlung model.

g. Measurements have been made of the breakdown threshold of mixtures of gases to study the effects of controlled impurities on the breakdown threshold. As little as 1 per cent neon added to argon reduces the breakdown threshold of the mixture to two-thirds the threshold of argon alone. From the pressure and volume dependence of the breakdown, a model to explain the reduced optical frequency breakdown threshold of the argon-neon mixture has been constructed. From the results obtained, it appears, as first proposed by Zel'dovich

and Raizer,[12] that excitation constitutes a loss process in the development of breakdown, and on the basis of the model of the gas mixture breakdown, radiative transport of this excitation energy from the breakdown volume is the diffusion-like loss process observed with the pure gases and the gas mixtures.

h. High-speed framing and streak photographs of the gas breakdown have been taken both during and after the giant laser pulse to determine the growth and lifetime of the breakdown plasmas. When initially formed, the plasma expands rapidly from its point of origin toward the incident laser beam at a velocity of 5×10^6 cm/sec. This rapid initial growth is followed by a slow contraction and a subsequent re-expansion accompanied by a decay of the breakdown luminosity. The transverse expansion of the breakdown is at all times slow compared to the initial rapid axial expansion, and after the termination of the laser pulse, the breakdown volume expands cylindrically with a diameter one-third its length. The breakdown volume has a long, narrow central core of high intensity which persists for times of the order of microseconds following the breakdown. Two theoretical models have been proposed to explain the rapid axial growth: (1) the energy-supported blast wave, where the laser energy is supplied to the existing breakdown plasma, and (2) breakdown propagation in which the laser beam intensity, increasing with time, becomes sufficiently high at successive points toward the incident laser beam to produce breakdown. In breakdown using large focal length lenses, the latter mechanism has been observed experimentally. Individual breakdowns are observed, separated in space and each propagating into the incident laser beam. The same mechanism may be involved in the short focal length breakdown propagation, but since the intensity decreases so rapidly away from the focal spot, the individual breakdowns are not observable.

i. Breakdown threshold measurements in cesium vapor at approximately 1 torr using ruby and neodymium laser radiation have been carried out to test the incremental photon absorptions predicted by the quantum mechanical inverse bremsstrahlung energy absorption mechanism. It was found that the ratio of the breakdown threshold power for cesium to that for argon is approximately 50 times less than that predicted by the classical microwave model of energy absorption. These results indicate that the rate of energy addition for a process requiring only 3 or 4 photon increments of energy is greater than that predicted for a many-step process. It was also determined experimentally that the breakdown thresholds of cesium vapor with ruby and neodymium laser radiation were approximately equal. This result shows that the cesium breakdown differs from that in the inert gases, since for the inert gases the threshold due to ruby radiation was twice that with neodymium radiation at atmospheric pressure, as predicted by the classical microwave model.

j. The breakdown threshold of argon with small added percentages of cesium vapor has been studied to determine the effects of impurities on the gas breakdown process. For atmospheric argon with a 10^{-3} torr cesium, the threshold power required to produce breakdown was reduced by a factor of two below that required for pure argon. The threshold reduction is due to ionization of the easily ionizable cesium and shows the importance of a low impurity level contamination on the breakdown process. Higher levels of cesium impurity (up to 1 torr) in atmospheric argon, while reducing the threshold of pure argon, did not result in as low a threshold as that determined with 10^{-3} torr cesium.

k. Breakdown produced by focusing the neodymium laser radiation in an argon electrical discharge was used to study the effects of an initial ionization on the breakdown process. Over the pressure range from 25 torr to atmospheric pressure, the breakdown threshold power required in the discharge was a factor of two less than that required for pure argon, the comparison for equal pressures. Based on the discharge voltage and current density, the electron density in the discharge was estimated to be in the range of 10^9 to 10^{11} cm^{-3}. The observed reduction in threshold with the initial ionization is consistent with the cascade growth of breakdown. In gas breakdown without the discharge, it is necessary for the ionization to grow from a very small initial ionization (most likely due to easily ionizable impurities) to full ionization of 10^{19} atoms cm^{-3} at atmospheric pressure. However, by starting with an initial electron concentration of 10^{11} cm^{-3}, the threshold power should be reduced by a factor of approximately two since one-half of the ionization generations necessary for full ionization have already been realized. The experimental observations further support the cascade growth process of gas breakdown.

l. The effects of the mode structure of the laser beam on the gas breakdown threshold have been investigated using laser pulses with two different mode structures: (1) temporally smooth multiple-mode neodymium laser pulses as used in previous experiments,[1-10] and (2) mode-locked pulses with well-defined intensity spikes caused by phase-locking of the laser cavity modes with a saturable dye Q-switch. With multiple mode lasers, interference between various modes in the focal region can lead to large localized electric fields which could be the cause of breakdown rather than the temporally and spatially averaged field strengths measured experimentally. The mode-locked laser pulses consist of a train of high-intensity short pulses, in which the peak intensities are several orders of magnitude larger than the average intensity of the pulse train. Despite the high-intensity fluctuations with the mode-locked pulses, the average power density required for breakdown with this pulse was found to be identical with that for the temporally smooth neodymium

laser pulses. Based on this result, it is concluded that the breakdown threshold of gases by optical frequency radiation is independent of the mode structure of the laser radiation source, and the threshold is adequately described by the temporally and spatially averaged intensities measured experimentally.

These experimental measurements also show that the multiple photon absorption process is not important in the development of gas breakdown. For the multiple photon process, the ionization rate is proportional to the joint probability of absorption of the n photons required to ionize an atom, and thus the ionization rate is proportional to the nth power of the radiation intensity. If the multiple photon theory were responsible for gas breakdown, slight variations in the laser beam intensity would produce large changes in the ionization rate and thus significant changes in the breakdown threshold. Since the intensity fluctuations with the mode-locked pulses did not materially affect the breakdown threshold, it is concluded that a multiple photon absorption process does not contribute to breakdown development.

m. Using a Mach-Zehnder interferometer, studies have been made of the growth and persistence of the breakdown plasma density and of the blast wave produced by gas breakdown. From the interferometric studies it was determined that the plasma is opaque to laser radiation for times as long as 100 nsec after breakdown. The attenuation of the He-Ne laser beam milliseconds after breakdown, described in paragraph b, is due to the turbulent heated gas in the breakdown region observed with the interferograms. At times 1-2 microseconds after breakdown initiation, the blast wave generated by the breakdown and observed in the interferograms is described by the Taylor strong blast wave theory.[19] The theory predicts the growth of the blast wave as $r = (\epsilon/\rho)^{1/5} t^{2/5}$ where r is the radial position at time t, ϵ is the absorbed laser energy, and ρ is the initial gas density, and describes the experimental blast wave position to within five per cent.

n. Investigations of the development of a high-power CO_2 laser with an output at 10.6-μ wavelength have been carried out. A $2\frac{1}{2}$-meter-long electrical discharge laser has been used to study the cw and rotating mirror Q-switched operation of the CO_2-N_2-He laser. With dc electrical excitation of the discharge, the maximum cw power obtained by optimizing the laser system variables was 125 watts. Using a rotating mirror Q-switch, giant pulses of 10-20 kilowatts were achieved. It was determined that heating of the discharge tube by the dc electrical discharge had a detrimental effect on the operation of the CO_2 laser. To eliminate these effects, a pulsed discharge power supply has been used to excite the laser system. With stationary mirrors, pulsed powers of 500 watts have been measured, a factor of four increase in laser output

compared with the dc electrical discharge laser. Synchronizing the rotating mirror with the electrical pulse, giant pulses containing five times the energy as those obtained with the dc excitation have been measured. Measurements are now being carried out to determine the pulse width and thus the power of the Q-switched, pulsed discharge laser system.

o. Passive Q-switching of the 10.6-μ CO_2 laser has been demonstrated. The bleachable element used was propane gas contained in a three-inch cell internal to the laser cavity. At a propane pressure of one atmosphere, the laser output consisted of irregular pulsed output with intensities much greater than the cw power level. Further studies are now under way to improve the operation of the passive Q-switch and to investigate other gases which may operate better than propane as a bleachable element.

2. Areas for Future Study

Section IV of this report described recent results in the development of a high-power 10.6-μ wavelength CO_2 laser. With the dc electrical discharge, 125 watts cw power was obtained. Q-switching with a rotating mirror produced giant pulses of 10 to 20 kilowatt intensity, well below the theoretically predicted power levels attainable from a 125-watt cw laser. The estimated power required for gas breakdown with 10.6-μ radiation is in the range of 100 kilowatts, which will require a considerable improvement of the existing Q-switched CO_2 laser system. During the next contract period experiments will be carried out to increase the CO_2 laser output, and these experiments are outlined briefly below:

1. The cw output of the CO_2 laser system can be increased by eliminating one sodium chloride window internal to the laser cavity, thereby reducing the laser cavity losses due to reflection. This will be accomplished by attaching the output mirror directly to the pyrex tube to form the gas seal. The use of improved optical components for 10.6-μ radiation, such as germanium, may also increase the laser output. Increase in the cw power output is a measure of increased gain of the laser system and therefore should also improve the Q-switched laser output power.

2. Studies of the laser output with a pulsed electrical discharge are presently underway. Pulsed laser powers five times greater than obtained with the dc electrical discharge laser have been measured. Investigations of the effects of the various laser parameters, such as mirror reflectance, gas mixture and pressure, and voltage pulse length, will be carried out to determine the optimum conditions for both pulsed and Q-switched operation of the pulsed discharge laser.

3. Further studies of a passive Q-switch for the CO_2 laser are being undertaken. Gases other than propane with absorption bands at 10.6 μ will be investigated. The length of the bleachable gas cell as well as the gas pressure are variables which will affect the absorption characteristics of the passive Q-switch, and the effects of these variables will be examined experimentally. Studies of Q-switching operation with the bleachable gas both alone and in concert with a rotating mirror will also be investigated, and the studies of the passive Q-switch will be conducted with both the dc and pulsed electrical discharge laser.

4. The gain of the pulsed discharge CO_2 laser is sufficiently high that superfluorescence has been observed, i.e., lasing action without the use of an output mirror. Further improvements in the CO_2 laser gain by the methods outlined above may be limited by this effect. If this proves to be the case, one solution is to use an oscillator-amplifier configuration. A giant pulse, produced in the oscillator, is passed through an amplifier whose maximum length will be limited by self-lasing. The oscillator-amplifier configuration has been used successfully for producing high-power optical frequency laser pulses and may also be required for high powers in the case of the 10.6-μ CO_2 laser.

VII. REFERENCES

1. Meyerand, R. G., Jr. and A. F. Haught, "Research on the Electrical Breakdown of Gases under Intense Optical Illumination," Final Report, January 1964, C-920088-2, prepared under Conrract Nonr-4299(00) for the Office of Naval Research, January 1964.

2. Haught, A. F., "Investigation of the Mechanisms Associated with Gas Breakdown under Intense Optical Illumination," Semi-Annual Report, December 1964, C-920272-2, prepared under Contract Nonr-4699(00) for the Office of Naval Research, December 1964.

3. Haught, A. F. and D. C. Smith, "Investigation of the Mechanisms Associated with Gas Breakdown under Intense Optical Illumination," Semiannual Report, August 1965, D920272-4, prepared under Contract Nonr-4699(00) for the Office of Naval Research, August 1965.

4. Haught, A. F. and D. C. Smith, "Investigation of the Mechanisms Associated with Gas Breakdown under Intense Optical Illumination," Semiannual Report, January 1966, E920272-6, prepared under Contract Nonr-4696(00) for the Office of Naval Research, January 1966.

5. Haught, A. F. and D. C. Smith, "Investigation of the Mechanisms Associated with Gas Breakdown under Intense Optical Illumination," Final Report, August 1966, E920272-8, prepared under Contract Nonr 4696(00) for the Office of Naval Research, August 1966.

6. Meyerand, R. G., Jr. and A. F. Haught, "Gas Breakdown at Optical Frequencies," Proceedings of the Sixth International Symposium on Ionization Phenomena in Gases, Paris, July 1963.

7. Meyerand, R. G., Jr. and A. F. Haught, "Gas Breakdown at Optical Frequencies," Physical Review Letters, Vol. 11, No. 9, November 1, 1963.

8. Meyerand, R. G., Jr. and A. F. Haught, "Optical-Energy Absorption and High-Density Plasma Production," Physical Review Letters, Vol. 13, No. 1, July 6, 1964.

9. Haught, A. F., Meyerand, R. G., Jr. and D. C. Smith, "Electrical Breakdown of Gases by Optical Frequency Radiation," Proceedings of Quantum Electronics Conference, P. L. Kelley, B. Lax, and P. E. Tannenwald (Eds.), McGraw-Hill Book Company, New York, 1966, p. 509.

10. Smith, D. C. and A. F. Haught, "Energy-Loss Processes in Optical Frequency Gas Breakdown," Physical Review Letters, Vol. 16, No. 24, June 13, 1966.

11. Smith, D. C. and R. G. Tomlinson, "Effect of Mode Beating in Laser Produced Gas Breakdown," to be published in the Applied Physics Letters, August 1967.

12. Zel'dovich, Ya. B. and Yu. P. Raizer, "Cascade Ionization of a Gas by a Light Pulse," Soviet Physics JETP, Vol. 20, No. 3, March 1965.

13. Phelps, A. V., "Theory of Growth of Ionization During Laser Breakdown," Proceedings of Quantum Electronics Conference, P. L. Kelley, B. Lax, and P. E. Tannenwald (eds.), McGraw-Hill Book Company, New York, 1966, p. 538.

14. Meadors, J. G., "Coherence Effects in Multiphoton Absorption Processes," IEEE Journal of Quantum Electronics, Vol. QE-2, No. 9, September 1966.

15. Bebb, H. B. and A. Gold, "Multiphoton Ionization of Rare Gas and Hydrogen Atoms," Proceedings of Quantum Electronics Conference, P. L. Kelley, B. Lax, and P. E. Tannenwals (eds.), McGraw-Hill Book Company, New York, 1966, p. 489.

16. Stetser, D. A. and A. J. DeMaria, "Optical Spectra of Ultrashort Optical Pulses Generated by Mode-Locked Glass:Nd Lasers," Applied Physics Letters, Vol. 9, No. 3, August 1, 1966.

17. Tozer, B. A., "Theory of the Ionization of Gases by Laser Beams," Physical Review, Vol. 137, No. 6A, March 15, 1965.

18. Keldysh, L. V., "Ionization in the Field of a Strong Electromagnetic Wave," Soviet Physics, JETP, Vol. 20, No. 5, May 1965.

19. Taylor, G. I., "The Formation of a Blast Wave by a Very Intense Explosion," Proceedings of the Royal Society, Vol. A201, 1950.

20. Flynn, G. W., Kovacs, M. A, Rhodes, C. K., and A. Javan, "Vibrational and Rotational Studies Using Q-Switching of Molecular Gas Lasers," Applied Physics Letters, Vol. 8, No. 3, February 1, 1966.

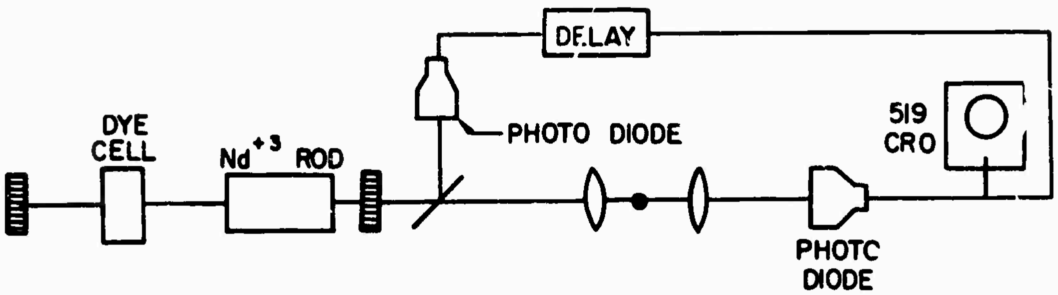
21. Flynn, G. W., Hocker, L. O., Javan, A., Kovacs, M. A. and C. K. Rhodes, "Progress and Applications of Q-Switching Techniques Using Molecular Gas Lasers," IEEE Journal of Quantum Electronics, Vol. QE-2, No. 9, September 1966.

VIII. LIST OF FIGURES

F-920272-10

FIG. 1

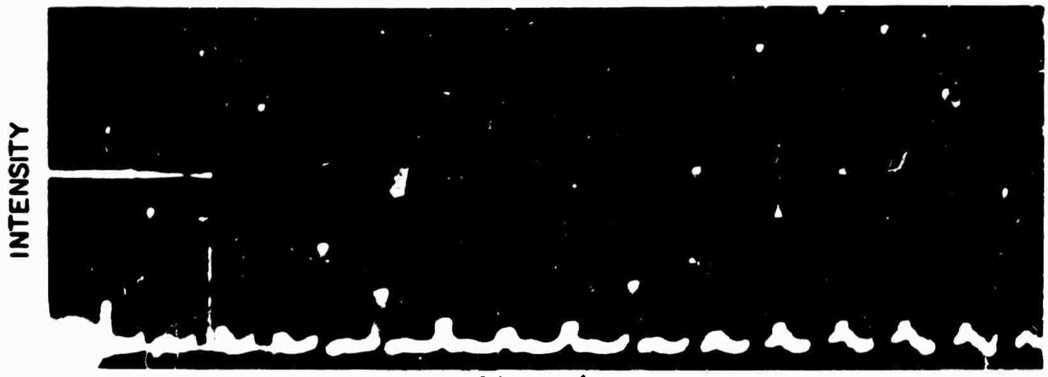
DYE CELL Q-SWITCHED LASER PULSE



APPARATUS SCHEMATIC

TRANSMITTED PULSE

INCIDENT PULSE

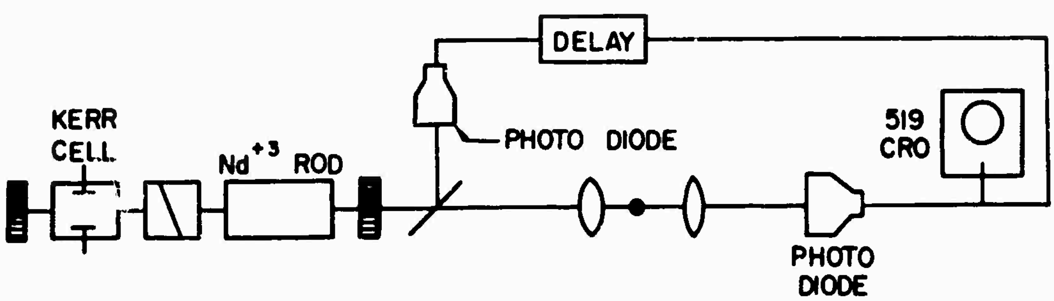


20 nsec/div

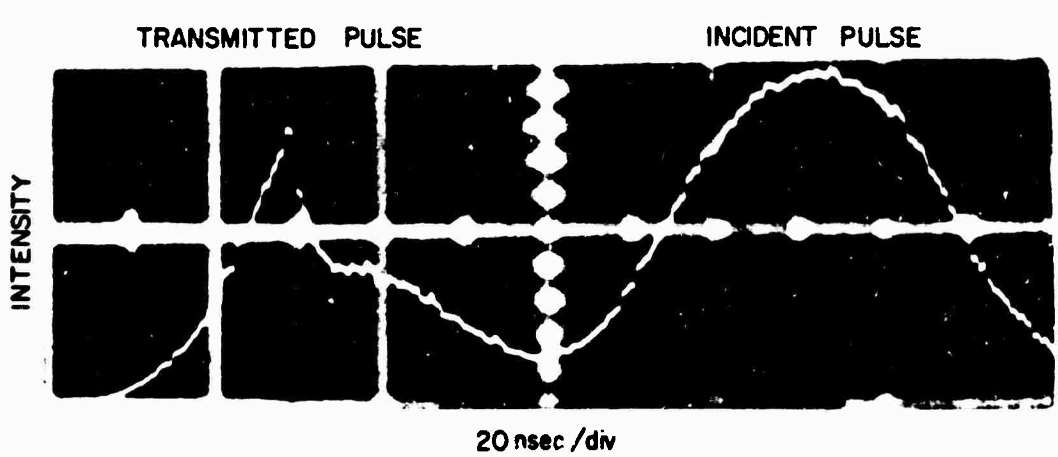
F-920272-10

FIG. 2

KERR CELL Q-SWITCHED LASER PULSE

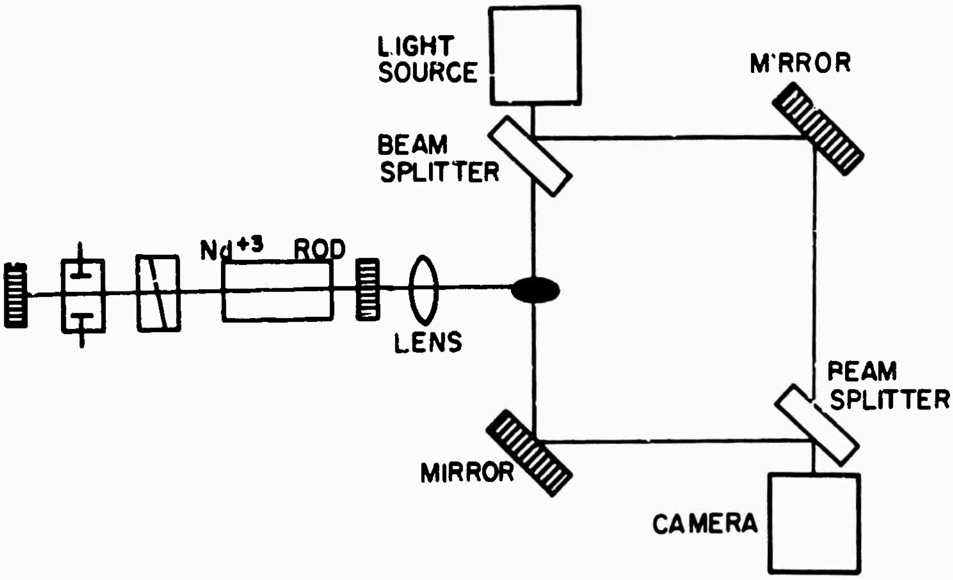


APPARATUS SCHEMATIC



F-920272-10 FIG. 3

INTERFEROGRAMS OF AIR BREAKDOWN



APPARATUS SCHEMATIC

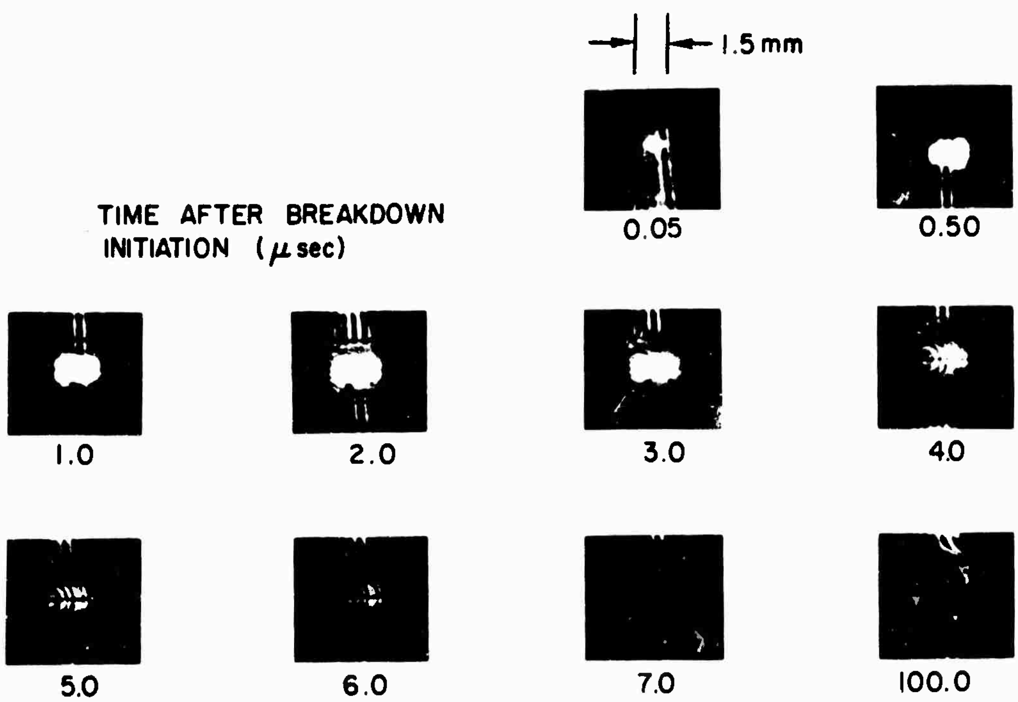


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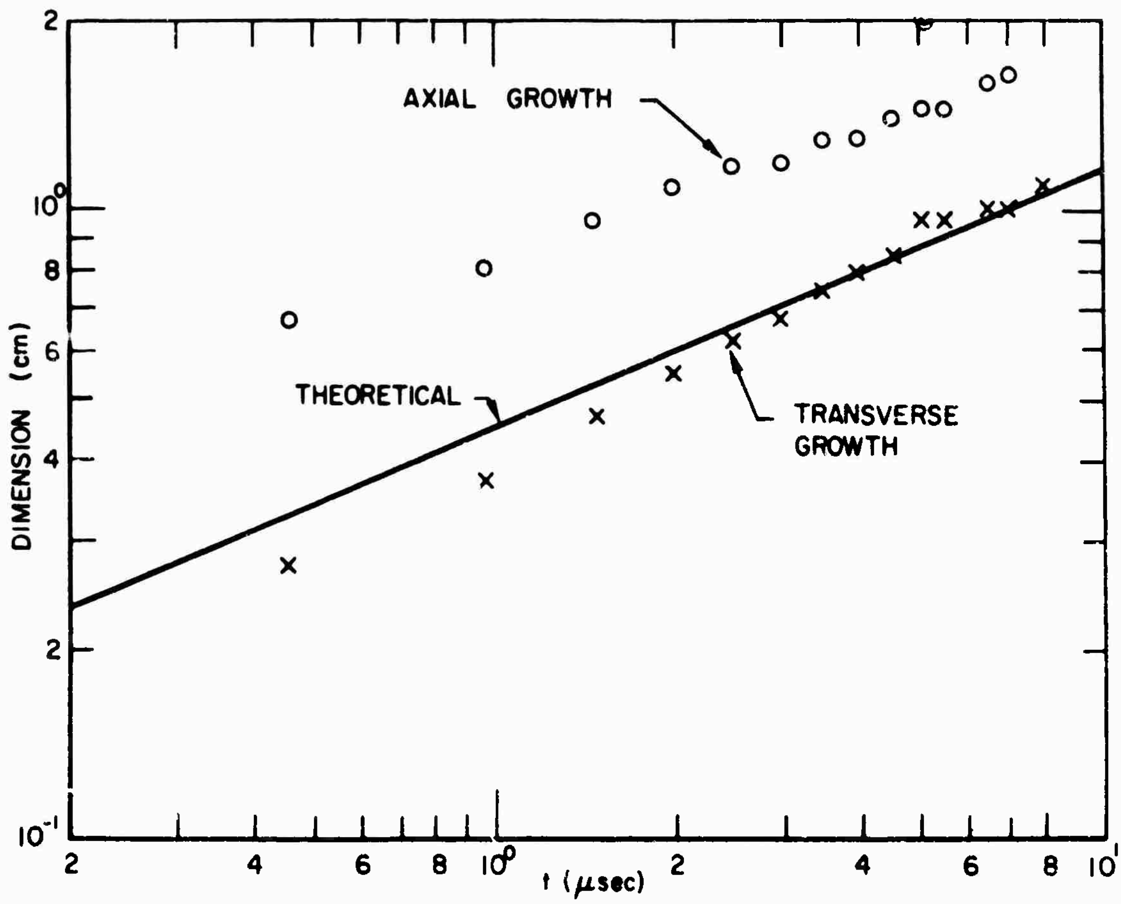
FIG. 4

AXIAL AND TRANSVERSE GROWTH OF BREAKDOWN BLAST WAVE



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SCHEMATIC OF CO_2 LASER SYSTEM

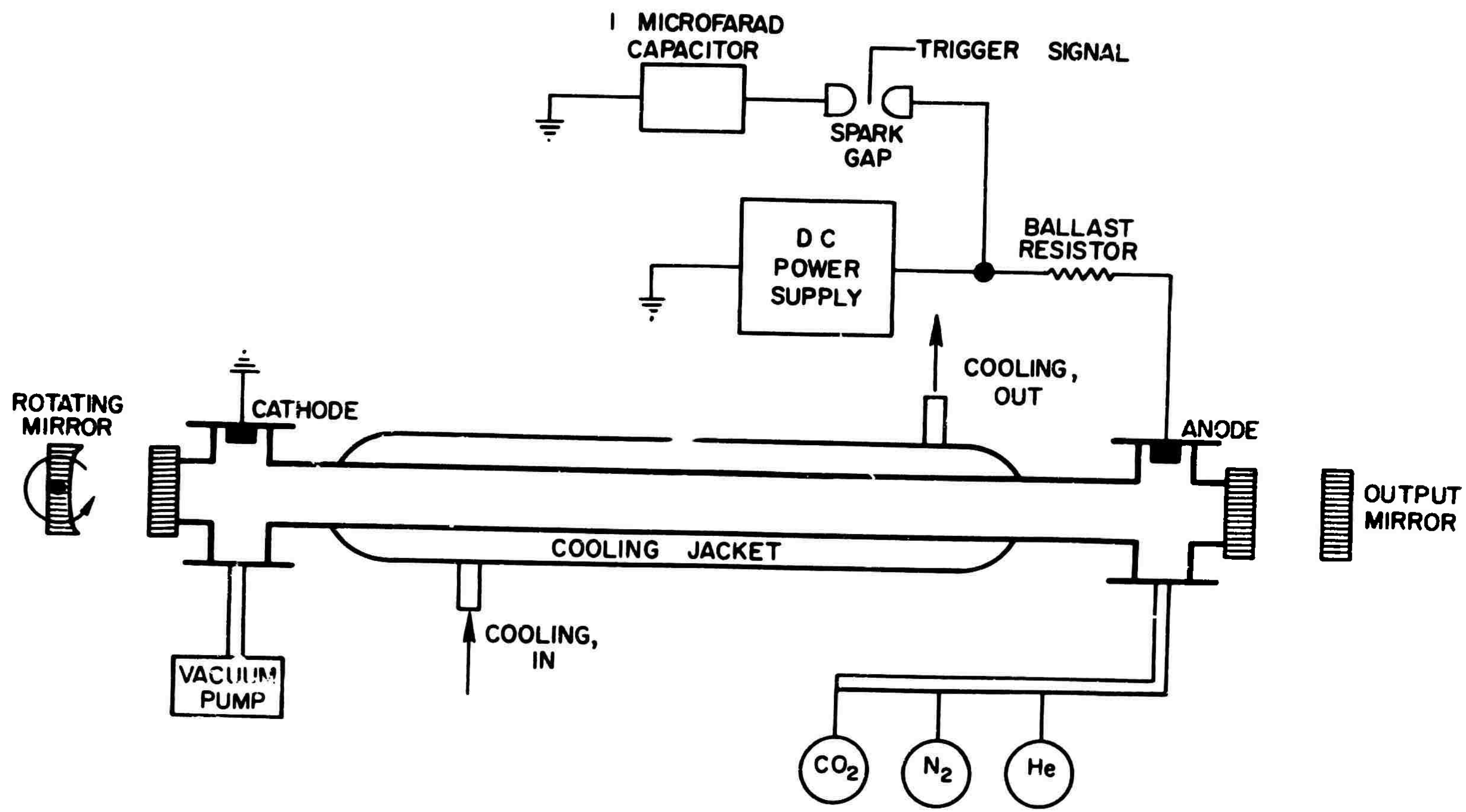

FIG. 5

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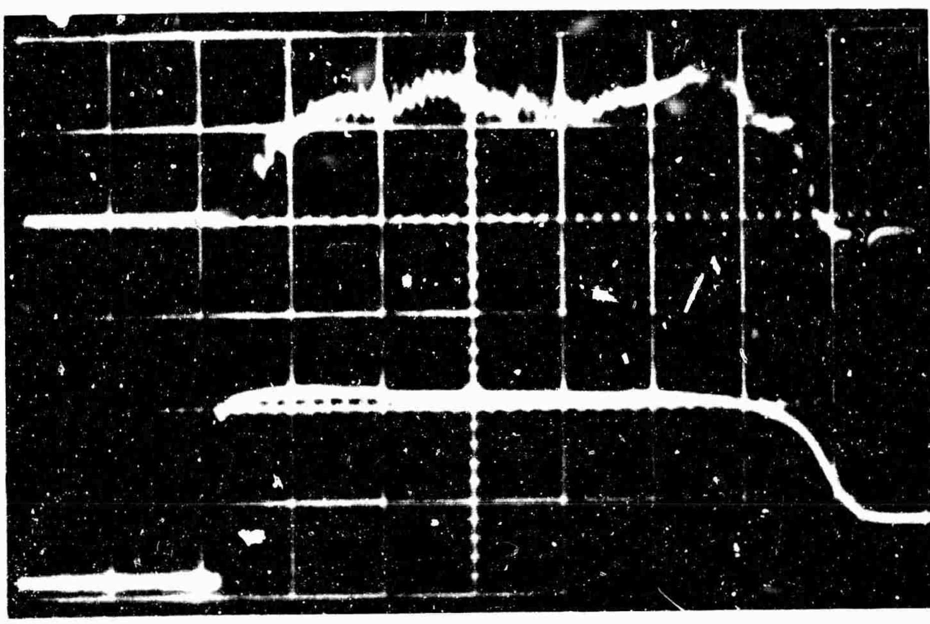
PULSED CO_2 LASER



LASER INTENSITY

VOLTAGE PULSE (10^4 V/div)

100μsec/div